Probing Sagittarius A* and its Environment at the Galactic Centre: VLT and APEX Working in Synergy

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On 3 June 2008 an international team of researchers observed one of the brightest near-infrared flares close to SgrA*, the black hole at the centre of the Milky Way. For the very first time the flare emission was detected in infrared light, with one of the VLT telescopes, and time delayed in sub-millimetre radiation with the APEX telescope. Recent simultaneous X-ray and infrared flares from SgrA* have been detected and can be explained by spots on relativistic orbits around the central, accreting supermassive black hole. The observations of flares now also show some evidence for time evolution of the spot properties. The investigation of dusty stars and filaments in the central stellar cluster also indicates the presence of a wind from the central region – possibly with a contribution from SgrA* itself.

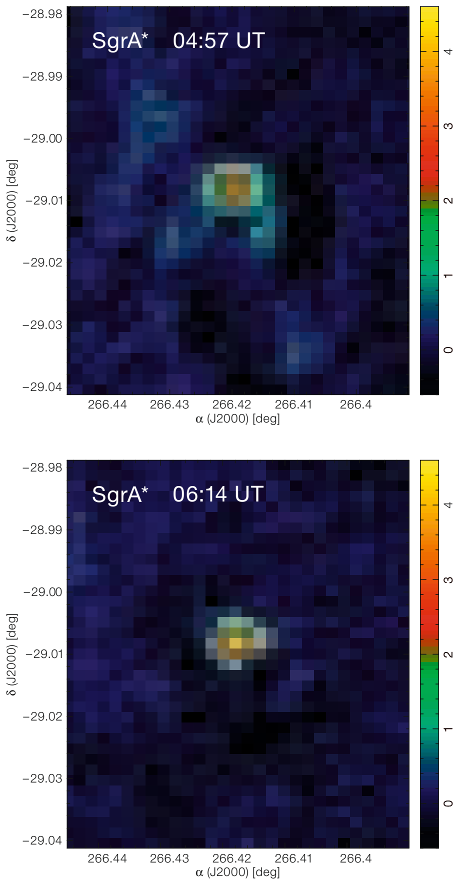
At the centre of the Milky Way, at a distance of only about 8 kpc, stellar orbits have convincingly proven the existence of a supermassive black hole (SMBH) of mass ~ 3.7×10^6 $M_\odot$ at the position of the compact radio, infrared, and X-ray source Sagittarius A* (SgrA*; see Eckart et al., 2002; Schödel et al., 2002; Eisenhauer et al., 2003; Ghez et al., 2005; and following publications). Additional strong evidence for an SMBH at the position of SgrA* comes from the observation of rapid flare activity both in the X-ray and near-infrared (NIR) wavelength domain (Baganoff et al., 2001; Genzel et al., 2003; Ghez et al., 2004; Eckart et al., 2006).

On account of its proximity, SgrA* provides us with a unique opportunity to understand the physics and possibly the evolution of SMBHs in the nuclei of galaxies. Variability at radio through sub-millimetre (sub-mm) wavelengths has been studied extensively, showing that variations occur on timescales from hours to years (e.g. Mauerhan et al., 2005; Eckart et al., 2006a; Yusef-Zadeh et al., 2008; Marrone et al., 2008). Several flares have provided evidence for decaying mm and sub-mm emission following NIR/X-ray flares.

The combined APEX/VLT measurements

The sub-mm regime is of special interest for simultaneous flare measurements. Here synchrotron source components that radiate also in the infrared domain become optically thick, and represent the dominant reservoir of photons that are then scattered to the X-ray domain through the inverse Compton process. Substantial progress was made during a global observing session on SgrA* in May/June 2008. On 3 June, for the first time, observations of the Galactic Centre were performed with ESO telescopes operating in the NIR and sub-mm wavelength domains, that resulted in the simultaneous successful detection of strongly variable emission. Such a clear detection with ESO telescopes at both wavelengths had not been achieved in several previous attempts. It was made possible through a special effort by the APEX/ONSALA staff to have the LABOCA bolometer ready for triggering.

At an angular resolution of 100 milliarcseconds, *K*- and *L′*-band (2.2 μm and 3.8 μm respectively) images were taken with the NAOS/CONICA adaptive optics assisted imager at VLT UT4 (Yepun). The calibrated images were deconvolved using a Lucy-Richardson algorithm. Submillimetre data were taken with LABOCA on APEX. The Atacama Pathfinder Experiment (APEX) is a new-technology 12-m telescope, based on an ALMA (Atacama Large Millimeter Array) prototype antenna, and operating at the Llano de Chajnantor at an altitude of 5105 m. APEX is a collaboration between the Max-Planck-Institut für Radioastronomie, the Onsala Space Observatory and ESO.



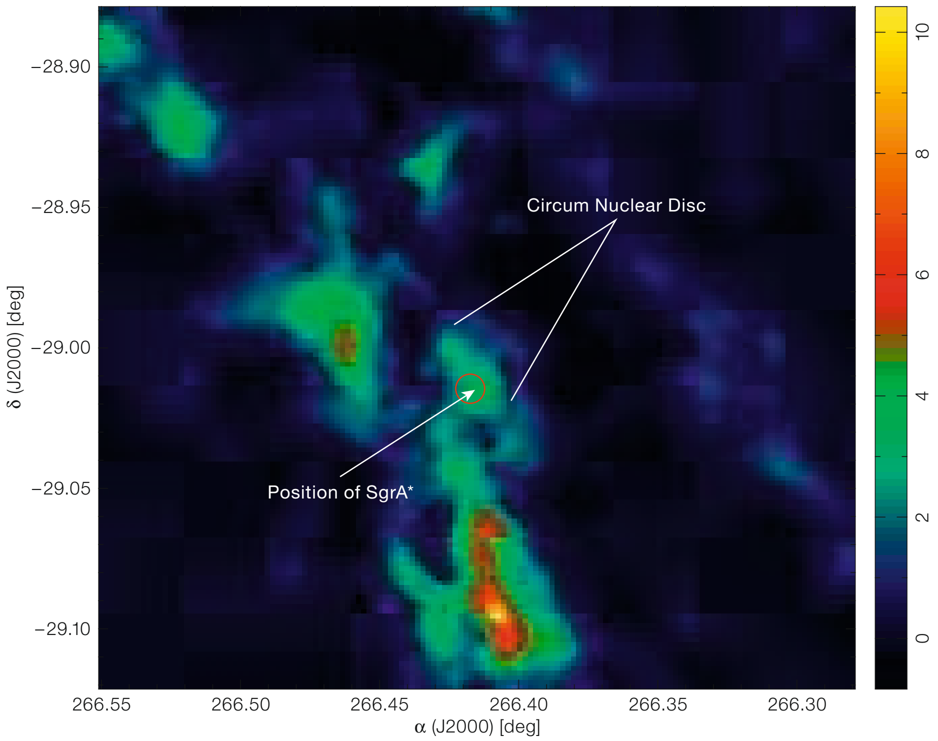


Figure 1 (above). **Left:** Sagittarius A* at the beginning and the peak of the APEX measurements. **Right:** A section of the larger map of the Galactic Centre. The location of Sagittarius A* is indicated by a circle. The colours code the flux density in Janskys.

The radiation collected by the APEX telescope is directed to the LArge BOlometer CAmera (LABOCA) in the Cassegrain cabin. LABOCA consists of an array of 295 composite bolometers, which are cooled to a temperature of less than 0.3 K, and are very sensitive to continuum radiation (see Siringo et al., 2007). With a total bandwidth of about 60 GHz the system is optimised for the 345 GHz atmospheric window. The final relative calibration was obtained by comparison to and subtraction of a high signal-to-noise reference map in which SgrA* was subtracted out and therefore effectively set in an off state (see Figure 1 right). The resulting light curves are shown in Figure 2. Each data point of the sub-mm light curve was derived from a full 48′ × 25′ fully sampled map obtained with the 19.2″ APEX beam.

The combined *K*- and *L*′-band data (Figure 2) show violently variable emission with at least four prominent flare events (I–IV). The sub-mm data start with a low flux density at the time of the first NIR flare. The gap in the sub-mm data occurred during culmination of SgrA*, when the source rises above the elevation limit (80°) for observations with APEX. A preliminary model fit to the variable sub-mm emission is shown in comparison to the data in Figure 2. We attribute the time difference between the NIR and sub-mm flares to an adiabatic expansion of synchrotron source components with an expansion speed of about 0.5 % of the speed of light (1500 km/s). With a spectral index between the sub-mm and the

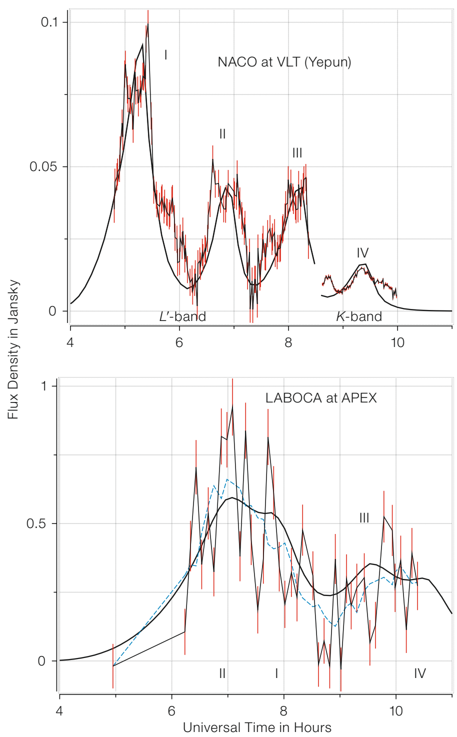


Figure 2 (right). The near-infrared (top) and sub-mm (bottom) light curve of Sagittarius A*. The data points are represented by vertical red bars (with ± 1σ error bars) with a black connecting line between them. The dashed line represents a smoothed version of the data (after application of a seven point sliding average for all data points except the first). The model – as described in the text – is shown as a thick solid line. To select the intra-day variable part of the sub-mm data, a flux density of 3.25 Jy has been subtracted. This amount is attributed to more extended (many Schwarzschild radii) source components.

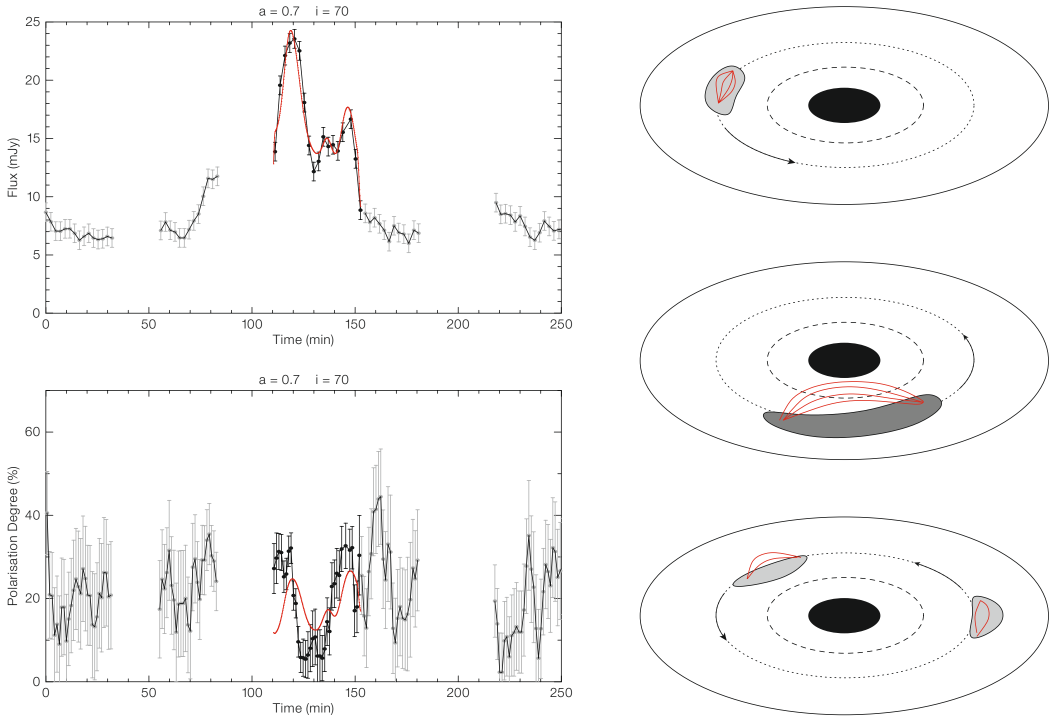


Figure 3. Left: Fit of the 2006 flare data with an evolving spot model. We show the total flux and degree of polarisation for a single spot during two revolutions for a perpendicular E-field configuration (for details see Eckart et al., 2008). Right: Sketch of an expanding hot spot within an inclined temporary accretion disc of SgrA*. The black centre indicates the event horizon of the massive black hole; the solid line the outer edge of the accretion disc. The long dashed line marks the inner last stable orbit. The dotted line represents a random reference orbit to show the effect of differential rotation of an extended emission region. The red solid line across the grey shaded extended spots depict the magnetic field lines that, through magneto-hydrodynamical instabilities, provide a coupling between disc sections at different radii.

infrared of about $-0.8 \leq \alpha \leq -1.4$, we find that the flares are associated with source components that have sizes of the order of one Schwarzschild radius and spectra that peak around 1–3 THz with flux densities of a few Janskys. In the sub-mm domain the flares blend with each other. Models with significantly different expansion speeds or source sizes fail to represent either the extent or the shape of the observed flare features. These data show that the VLT/APEX combination is especially well suited for very long simultaneous light curves between the NIR and the sub-mm domain.

The adiabatic expansion results in a time difference between the peaks in the VLT and APEX light curves of about 1.5 to 2 hours. This compares well with the values obtained in a global, multi-wavelength observing campaign by our team in 2007. Two bright NIR flares were traced by CARMA (Combined Array for Research in mm-wave Astronomy; 100 GHz) in the US, ATCA (Australia Telescope Compact Array; 86 GHz) in Australia, and the MAMBO bolometer at the IRAM 30-m in Spain (230 GHz; first results given by Kunneriath et al., 2008). This light curve complements our parallel 13, 7, and 3 mm VLBA run (Lu et al., 2008).

Simultaneous multi-wavelength observations indicate the presence of adiabatically expanding source components with a delay between the X-ray and sub-mm flares of about 100 minutes (Eckart et al., 2006a; Yusef-Zadeh et al., 2008; Marrone et al., 2008). From modelling the mm-radio flares at individual frequencies, Yusef-Zadeh et al. (2008) invoke expansion velocities in the range from v_{exp} = 0.003 – 0.1 c, which is small compared to the expected relativistic sound speed in orbital velocity in the vicinity of the SMBH. The low expansion velocities suggest that the expanding gas cannot escape from SgrA* or must have a large bulk motion (Yusef-Zadeh et al., 2008). Therefore the adiabatically expanding source components either have a bulk motion larger than v_{exp} or the expanding material contributes to a corona or disc, confined to the immediate surroundings of SgrA*.

Polarised emission from an accretion disc?

X-ray and polarised infrared emission of flares allow an even deeper insight into the processes that show some of their dominant signatures in the sub-mm domain. Recent NIR polarisation measurements have revealed that the emission of SgrA* is significantly polarised during flares. It consists of a non- or weakly-polarised main flare with highly polarised sub-flares (Eckart et al., 2006a; Meyer et al., 2007 and references therein). These are the first NIR polarimetric observations of a source clearly operating in the strong-gravity regime. Therefore they are important to test general relativity models of accreting SMBHs. In several cases the flare activity suggests a quasi-periodicity of ~ 20 min. By simultaneous fitting of the light curve fluctuations and the time-variable polarisation angle, we show that the data can be successfully modelled with a simple relativistic hot spot/ring model. In this model the broad NIR flares (~ 100 minutes duration) of SgrA* are due to a sound wave that travels around the SMBH once. The sub-flares, superimposed on the broad flare, are then caused by the Doppler-boosted spot emission, which is thought to be due to transiently heated and accelerated electrons of a plasma component. Recent investigations of infrared light curves show that significant contributions due to a red noise process (i.e. larger amplitudes towards lower frequencies) are likely as well (Do et al., 2008; Meyer et al., 2008).

In the presence of an extended disc structure, such a contribution can also be modelled through multiple components with properties following power spectrum distributions (Eckart et al., 2008; and below). The spots would then be the brightest contributors to the overall flux density. Scenarios in which spiral wave structures contribute to the observed variability are also under discussion (e.g. Karas et al., 2007).

VLT and Chandra provide indications for spot evolution

The May 2007 polarimetric NIR measurements showed a flare event with the highest sub-flare contrast observed until now. In the relativistic disc model these data provide direct evidence for a spot expansion and its shearing due to differential rotation (Figure 3). An expansion by only 30 % will lower the Synchrotron-Self-Compton (SSC) X-ray flux significantly. Therefore this scenario may explain the July 2004 flare (Eckart et al., 2006a) and possibly also the 17 July 2006 flare reported by Hornstein et al. (2007). In these events a strong NIR/X-ray flare was followed by a weaker NIR flare with no X-ray activity.

In summary, a combination of a temporary accretion disc with a short jet can explain most of the properties associated with infrared/X-ray SgrA* light curves (Eckart et al., 2008). The close correlation between the NIR and X-ray flares can be explained by combining relativistic amplification curves with a simple SSC mechanism. This explanation allows a zeroth order interpretation within a time-dependent flare emission model. We use a synchrotron model with an optically thin spectral index of $0.4 \leq \alpha \leq 1.3$ and relativistic electrons with boosting factor $\gamma_e \sim 10^3$. The source component flux densities are represented by a power spectrum $N(S) \propto S_m^{\alpha_S}$ with α_S close to –1. Such a multi-component model explains possible quasi-periodic sub-flare structure at infrared wavelengths, and shows that with adequate sensitivity and time resolution they should be detectable in the X-ray domain as well.

Further simultaneous radio/sub-mm data, NIR *K*- and *L*-band measurements in combination with X-ray observations should lead to a set of light curves that will allow us to prove the proposed model and to discriminate between the individual higher and lower energy flare events. Here Chandra's high angular resolution is ideally suited to separate the thermal non-variable bremsstrahlung from the non-thermal variable part of the SgrA* X-ray flux density for weak flares.

Indications for an outflow from Sagittarius A*?

Well within the central stellar cluster (Schödel et al., 2007), *L′*-band (3.8 μm) images of the Galactic Centre show a large number of long and thin filaments in the mini-spiral, located west of the mini-cavity and along the inner edge of the Northern Arm (Figure 4). Mužić et al. (2007) present the first proper motion measurements of these filaments and show that the shape and motion of the filaments do not agree with a purely Keplerian motion of the gas in the potential of the SMBH. The authors argue that the properties of the filaments are probably related to an outflow from a disc of young mass-losing stars or (in part) from the SMBH itself. In addition Mužić et al. (2007) also present the proper motions of two cometary shaped dusty sources close (in projection) to SgrA* (Figure 4). The proper motion of the stars X7 and X3 are at large angles to its V-shape. Therefore these dust shells indicate an interaction with a fast wind in the Galactic Centre ISM. The V-shapes of both sources are pointed towards the position of SgrA* and therefore represent the most direct indication for a wind from SgrA*. The wind responsible for the V-shape of the sources may in fact be the same wind that was claimed to be responsible for the formation of the mini-cavity in the mini-spiral.

Further evidence for young stars in the central cluster

The presence and formation of stars in the central parsec is a long standing problem. Only half an arcsecond north of IRS 13E there is a complex of extremely red sources, called IRS 13N. Their nature is still unclear. Based on the analysis of their colours, they may either be dust-embedded sources, older than a few Myrs, or extremely young objects with ages less than 1 Myr. Mužić et al. (2008) pre-sent the first proper motion measurements of IRS 13N members and give proper motions of four of IRS 13E stars resolved in NACO *L′*-band images. They show that six of seven resolved northern sources show a common proper motion, thus revealing a new comoving group of stars in the central half a parsec of the Milky Way. The common proper motions of the IRS 13E and IRS 13N clusters are also significantly different. By fitting the positional data for those stars onto Keplerian orbits, assuming SgrA* as the centre of the orbit, Mužić et al. (2008) could demonstrate that the IRS 13N association also indicates a dynamically

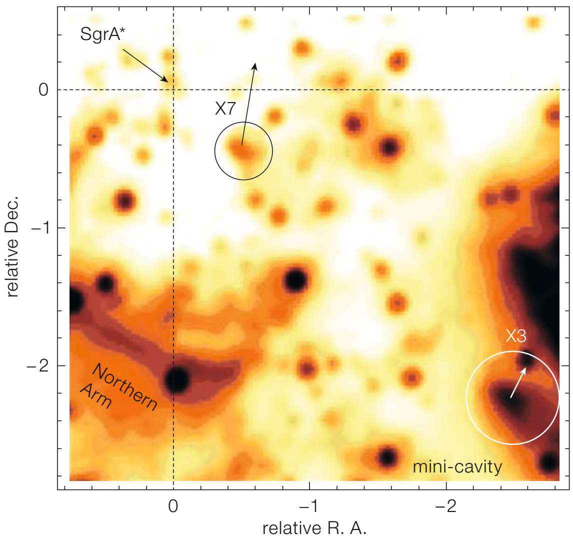


Figure 4. A 3.8″ × 3.8″ section of an *L′*-band image showing SgrA* and the two cometary shaped sources X3 and X7, which have proper motions of 155 ± 30 km/s and 463 ± 30 km/s respectively. The V-shaped dust shells indicate an interaction with a strong wind in the local Galactic Centre ISM. The V-shapes of both sources are pointed toward the position of SgrA*, suggesting that the wind originates in the immediate surroundings of SgrA*.

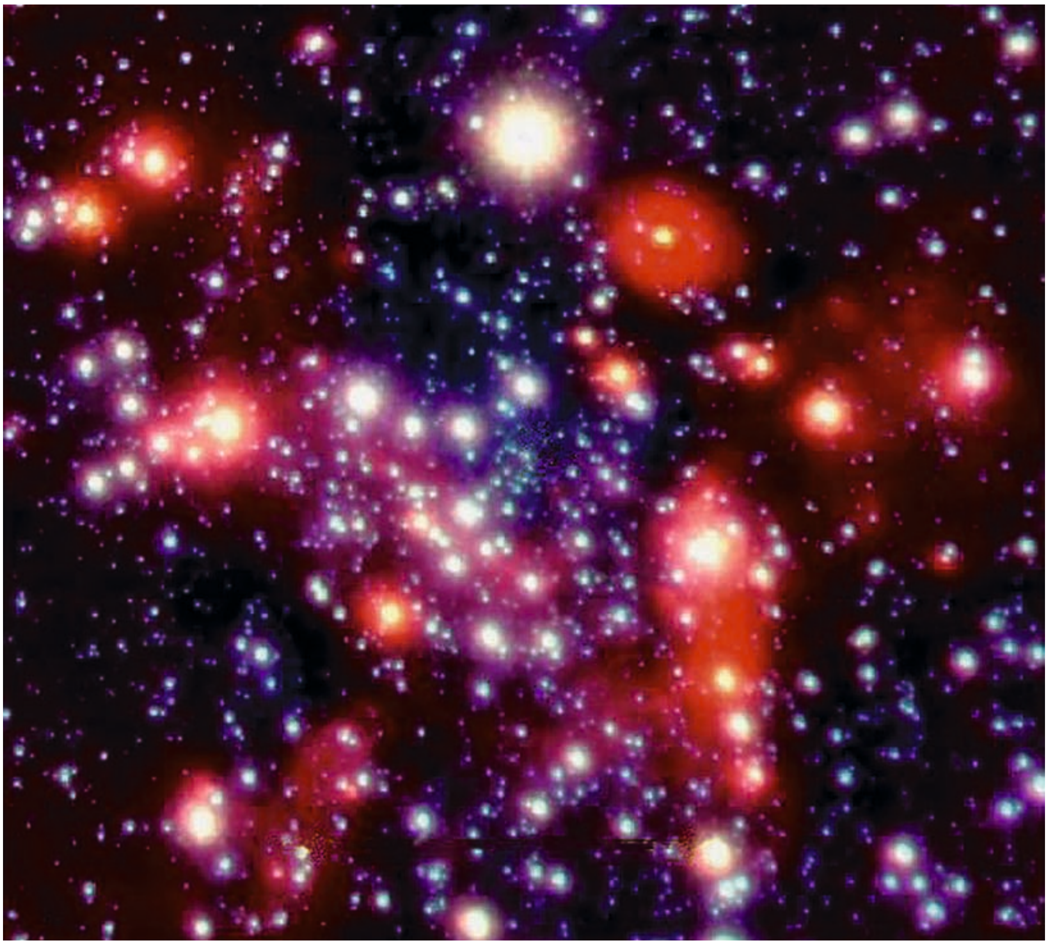
young system of stars and therefore is in favour of the very young star hypothesis.

New VLTI results in the central stellar cluster

In addition to the MIDI VLTI results on IRS 3 (Pott et al., 2008a), Pott et al. (2008b) now present the first spectro-interferometry on IRS 7, which is a prime reference source for Galactic Centre observations at the highest angular resolution. The VLTI-AMBER and MIDI instruments were used to spatially resolve IRS 7 and to measure the wavelength dependence of the visibility using the low spectral resolution mode ($\lambda/\Delta\lambda \sim 30$) and projected baseline lengths of about 50 m. The observations resulted in an angular resolution of about 9 mas (74 AU) and 45 mas (370 AU) for the NIR and MIR, respectively. The first *K*-band fringe detection of a star in the central parsec suggests that IRS 7 is possibly marginally resolved at 2 μm. At 10 μm wavelength, IRS 7 is strongly resolved with a visibility of approximately 20 % of the total flux density. This would imply that the photosphere of the supergiant is enshrouded by a molecular and dusty envelope.

References

Baganoff, F. K., et al. 2001, Nature, 413, 45
Do, T., et al. 2008, JPhCS, accepted and ApJ, submitted
Eckart, A., et al. 2008, A&A, 479, 625
Eckart, A., et al. 2006, A&A, 450, 535
Eckart, A., et al. 2002, MNRAS, 331, 917
Eisenhauer, F. 2003, ApJ, 597, L121
Genzel, R., et al. 2003, Nature, 425, 934
Ghez, A. M., et al. 2004, ApJ, 601, 159
Ghez, A. M., et al. 2005, ApJ, 620, 744
Karas, V., et al. 2007, Proceedings of the Workshop on Black Holes and Neutron Stars, eds. S. Hledik & Z. Stuchlik, 99 (astro-ph0709.3836)
Kunneriath, D., et al. 2008, JPhCS, accepted
Hornstein, S. D., et al. 2007, ApJ, 667, 900
Lu, R.-S., et al. 2008, JPhCS, accepted
Marrone, D. P., et al. 2008, ApJ, in press (arXiv0712.2877M)
Mauerhan, J. C., et al. 2005, ApJ, 623, L25
Meyer, L., et al. 2007, A&A, 473, 707
Meyer, L., et al. 2008, ApJ, submitted
Mužić, K., et al. 2008, A&A, 482, 173
Mužić, K., et al. 2007, A&A, 469, 993
Pott, J.-U., et al. 2008a, A&A, 480, 115
Pott, J.-U., et al. 2008b, A&A, in press (arXiv:0805.4408)
Schödel, R., et al. 2002, Nature, 419, 694
Schödel, R., et al. 2007, A&A, 469, 125
Siringo, G., et al. 2007, The Messenger, 129, 2
Yusef-Zadeh, F., et al. 2008, ApJ, accepted (arXiv0712.2882Y)



False colour near-infrared image of the central parsec of the Milky Way as obtained from data taken in the *H*, *Ks*, and *L′* filters with the VLT adaptive optics camera system NACO in 2004. Red sources are brighter at longer wavelengths. The image is dominated by the bright stars of the central star cluster and the diffuse emission of the dusty mini-spiral. Image credit: Rainer Schödel and Andreas Eckart.